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Solid-state anaerobic digestion for methane production from organic waste

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ABSTRACT

Solid-state anaerobic digestion (SS-AD) generally occurs at solid concentrations higher than 15%. In contrast, liquid anaerobic digestion (AD) handles feedstocks with solid concentrations between 0.5% and 15%. Animal manure, sewage sludge, and food waste are generally treated by liquid AD, while organic fractions of municipal solid waste (OFMSW) and lignocellulosic biomass such as crop residues and energy crops can be processed through SS-AD. Some advantages of SS-AD include smaller reactor capacity requirements, less energy used for heating, and no processing energy needed for stirring. Due to its lower water content, the digestate of SS-AD is much easier to handle than the effluent of liquid AD. However, SS-AD systems also have disadvantages such as larger amounts of required inocula and much longer retention time.

The principles and applications of the SS-AD process are reviewed in this paper. The variation in biogas production yields of different feedstocks is discussed as well as the need for pretreatment of lignocellulosic biomass to enhance biogas production. The effects of major operational parameters, including C/N ratio, solids content, temperature, and inoculation on the performance of SS-AD are summarized. While an increase in operating temperature can improve both the biogas yield and the production efficiency, other practices such as using AD digestate or leachate as an inoculant or decreasing the solid content, may increase the biogas yield but have negative impact on production efficiency. Different reactor configurations used in current commercial scale SS-AD systems and the impact of economics on system selection are also discussed.

Contents

1. Introduction

Anaerobic digestion (AD) is a method engineered to decompose organic matter by a variety of anaerobic microorganisms under

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oxygen-free conditions. The end product of AD includes biogas (60–70% methane) and an organic residue rich in nitrogen. This technology has been successfully implemented in the treatment of agricultural wastes, food wastes, and wastewater sludge due to its capability of reducing chemical oxygen demand (COD) and biological oxygen demand (BOD) from waste streams and producing renewable energy [1]. Already established as a reliable technology in Europe and Asia, AD is used to treat more than 10% of organic waste in several European countries [2]. AD processes are classified by critical operating parameters and reactor design such as continuity (batch versus continuous), operating temperature (psychrophilic, mesophilic and thermophilic), reactor design (plug-flow, complete-mix, and covered lagoons), and solid content (wet versus dry). Solid-state anaerobic digestion (SS-AD) is characterized by the high solid content of the feedstocks to be digested, which is typically greater than 15% [3]. Recent publications use different terminologies for SS-AD such as dry fermentation or dry digestion. The aforementioned terms will be referred to as SS-AD in this article.

SS-AD has been claimed to be advantageous over liquid AD for a number of reasons including smaller reactor volume, lower energy requirements for heating, minimal material handling, and lower total parasitic energy loss [4]. Biogas production from SS-AD is comparable to the output of liquid AD [5]. Due to its low moisture content, the digestate of SS-AD can be used as fertilizer or pelletized fuel, which is much easier to handle than the effluent of liquid AD. SS-AD technology currently provides approximately 54% of the total installed AD capacity in Europe, and the percentage of dry systems has been increasing since 2005 [6]. There are two full-scale SS-AD facilities in operation in North America that process MSW both near Toronto, Ontario in Canada [7]. There is no commercial scale SS-AD facility currently operating in the United States [7]. Only a few pilot scale SS-AD systems have been installed in the United States, such as the APS digester system installed by Onsite Power Systems Inc. (Davis, CA) in association with the University of California, Davis [3]. The commercial application of SS-AD is expected to increase in the US due to its economical and environmental benefits over current methods for treating or disposing MSW and other solid wastes such as incineration, landfill, and composting [8].

Despite the many advantages of SS-AD technology and progress in system designs, there are a number of aspects that need to be improved for further commercialization of the technology. The retention time of SS-AD has been documented to be up to three times longer than liquid AD due to the slower mass transportation in SS-AD than that of liquid AD. The improvement of production efficiency and economics is necessary, especially in regions where conventional techniques such as landfilling are still lower cost options [3]. Further improvements in feedstock preprocessing, digestate utilization, stability control, and reactor design are in demand. The objective of this study is to provide a comprehensive review of current SS-AD technology in respect to microbial communities, process, and reactor design.

2. Fundamental aspects

2.1. Basic reactions

AD is a synergistic process of a consortium of microbes which can be classified along with a series of metabolic pathways [9]. The major reactions of the AD process are shown in Fig. 1. At the beginning of the AD process, hydrolysis occurs reducing complex organic polymers to simple soluble molecules by extracellular enzymes. Proteins, lipids and carbohydrate polymers are hydrolyzed to amino acids, long-chain fatty acids, and sugars, respectively.

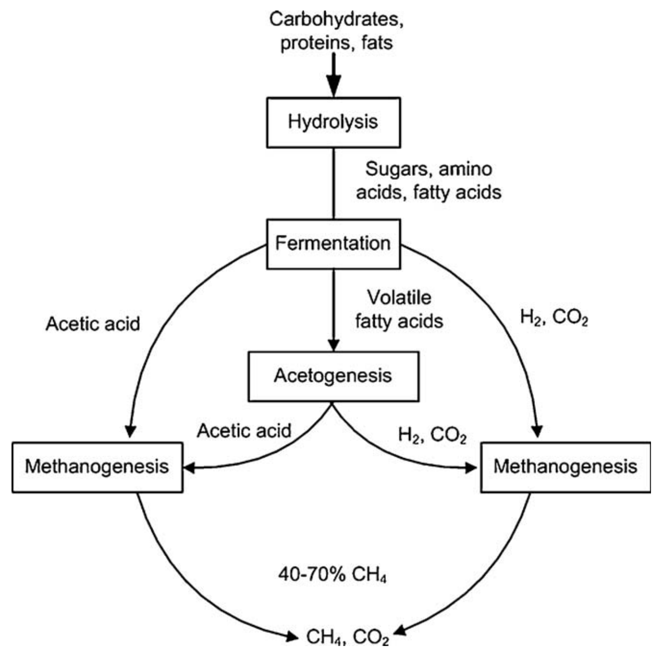

Fig. 1. Process flow of the degradation of organic material through anaerobic digestion.

The reduced compounds are then converted by fermentative bacteria to a mixture of short chain volatile fatty acids (VFAs) and other minor products such as carbon dioxide, hydrogen and acetic acid. Acetogenic bacteria further convert the organic acids to acetate, carbon dioxide, and/or hydrogen which are the direct substrates for methane production [10]. The final step of AD is methanogenesis, where a variety of methanogenic bacteria consume acetate, carbon dioxide, and hydrogen to produce methane. Methanogenesis is the focus of many AD studies due to its sensitivity to feedback inhibition by acidic intermediates.

2.2. Microbial communities

The microorganisms that function within the AD process can be mainly classified as hydrolytic, fermentative, acetogenic, and methanogenic [11]. In the hydrolysis phase, hydrolytic bacteria reduce complex particulate compounds to soluble monomeric or dimeric substrates. Generally, most of the soluble organic material in the reactor medium is converted to volatile organic acids through fermentation and eventually processed into biogas through methanogenesis [12]. Hence, hydrolysis is a critical rate-limiting step that determines the conversion efficiency of the biomass feedstock. Cellulose, found in many agricultural and municipal wastes, is an example of an insoluble compound that undergoes enzymatic hydrolysis. Cellulolytic bacteria such as *Cellulomonas*, *Clostridium*, *Bacillus*, *Thermomonospora*, *Ruminococcus*, *Baceriodes*, *Erwinia*, *Acetovibrio*, *Microbispora*, and *Streptomyces* can produce cellulases that hydrolyze cellulolytic biomass [13].

Fermentative bacteria are responsible for consuming the solubles created from hydrolysis and producing various intermediates such as VFAs, carbon dioxide, hydrogen gas and alcohols. Some of the fermentation pathways that occur during AD, along with their corresponding microorganisms, are shown in Table 1 [10]. Among the products of fermentation, acetate and carbon dioxide contribute the most to methane production.

Acetogenic bacteria, or acetogens, are differentiated from acetate-forming fermentative bacteria mainly because of their capability to reduce carbon dioxide to acetate by means of the Wood-Ljungdahl pathway. There are bacterial genera that are

Table 1
Major genera of fermentative bacteria in anaerobic digestion.

Fermentation pathway	Genera	Major products	Reference
Acetate fermentation	*Acetobacterium, Clostridium, Sporomusa*	Acetate, CO_2	[14–16]
Alcohol fermentation	*Saccharomyces*	Ethanol, CO_2	[17,18]
Butyrate fermentation	*Butyribacterium, Clostridium*	Butyrate, butanol, isopropanol, ethanol, CO_2	[19,20]
Lactate fermentation	*Lactobacillus, Streptococcus*	Lactic acid, CO_2	[18]
Propionate fermentation	*Clostridium*	Propionate, acetate, CO_2	[16]

exclusively acetogenic, such as *Acetobacterium* and *Sporomusa*, and there are also genera that contain both acetogenic and non-acetogenic bacteria, such as *Clostridium*, *Ruminococcus*, and *Eubacterium* [21]. A combination of the vital role of acetate as a methanogen substrate as well as the ubiquity and diversity of acetogens makes AD a naturally robust phenomenon. However, acetogens are obligate hydrogen producers that cannot survive in high partial hydrogen pressures, thus a symbiotic relationship exists between acetogens that produce hydrogen and methanogens that consume it [10].

The heterogeneous nature of the substrate in SS-AD systems might create a multiplicity of ideal micro-environments for the growth of each of the microbial families required to complete the process. Thus, fermentation processes that are well understood in conventional submerged culture can behave quite differently in solid substrates [22].

3. SS-AD process

3.1. Feedstocks

A wide range of organic solids found in municipal, industrial, and agricultural wastes can be used as SS-AD feedstocks. The composition and characteristics of solid wastes from different resources vary widely and significantly affect the performance of SS-AD such as start-up performance, retention time, biogas yield, and conversion ratio of total and volatile solids.

3.1.1. Food wastes

Food wastes contain high amounts of organic solubles that can be easily converted to VFAs. Excessive VFA conversion at an early stage of digestion may cause a drastic drop in pH and inhibit the methanogenesis process [23]. In order to reduce the inhibition of methane fermentation by organic acids produced rapidly at the initial stage of anaerobic digestion, co-digesting carbohydrate-rich feedstocks with other feedstocks or using a two-phase digestion system has been proven to be effective. Lu et al. [24] studied the co-digestion of dog food with woodchips and sludge with a total solid (TS) content of 43% at meso- and thermophilic conditions. In the first 2 weeks, pH decreased from 6.7 to 4.2 at 35 °C and to 5.8 at 55 °C because the original alkalinity (3000 mg/L as $CaCO_3$) was insufficient for pH buffering. Under these different conditions, the final dry mass conversion ratios were 48% and 50%, respectively. When mixed Korean food wastes with 20% TS were digested in a two-phase system at 37 °C, 87–90% of TS were reduced, approximately 90% of the initial volatile solid (VS) was converted to biogas, and the methane yield reached 86–88% of the biochemical methane potential (BMP) [23]. When 70% food waste, 20% fecal matter, and 10% green algae were co-digested at 39 °C, a biogas yield of up to 90% was obtained [25].

3.1.2. Agricultural wastes

Agricultural residues such as corn stover, wheat straw, and rice straw are promising feedstocks for SS-AD because of their plentiful supply, high potential biogas yields, and low costs. The carbohydrates in crop residues, which exist mostly as the polysaccharides cellulose and hemicellulose, are not readily available for immediate fermentation. Cellulose, hemicellulose, and lignin are covalently linked with each other which protect the potentially available carbohydrates from degradation.

Pretreatment is required for the utilization of carbohydrates in lignocellulosic biomass [25–27]. Over the years, a number of different methods, including dilute acid [28], steam explosion [29], lime [30], and ammonia [31,32] have been developed for the pretreatment of lignocellulosic biomass. The main purpose of pretreatment is to remove or alter the hemicellulose or lignin, decrease the crystallinity of cellulose, and increase the surface area [33].

Steam pretreatment of corn stover at 190 °C for 5 min using SO_2 as an acid catalyst has been shown to give high sugar yields (almost 90% overall glucose yield and almost 80% overall xylose yield) after 72 h of enzymatic hydrolysis [34]. Compared with untreated rice straw, water-soluble extractions of 6% NaOH-treated rice straw increased 122.5% and the biogas yield increased by 64.5% and 27.5% at the loading rates of 35 and 65 g/L, respectively [35]. In a separate study, 6% NaOH-treated corn stover digested at a loading rate of 65 g/L achieved 48.5% more biogas production, as compared to the untreated corn stover [36].

3.1.3. Organic fraction of municipal solid waste (OFMSW)

The composition of OFMSW varies widely ranging from food waste (vegetable waste or fruit peels) to yard waste (leaves or grasses). The strategy of waste collection affects the characteristics of OFMSW, biogas yield, and disposal (agricultural fields or landfill/incineration) of the digestate from the SS-AD process [37]. Changes in the composition of the separately collected organic fraction of municipal solid wastes (SC-OFMSW) occur during the year due to seasonal variations and differences in regional practices [38].

Biogas yield is substantially affected by the characteristics of OFMSW. Specific biogas production of 200 and 60 m^3/ton of treated waste, with a specific methane production of 0.4 and 0.13 m^3/kg of volatile solids (VS) fed to the reactor, were obtained with SS (source sorted)-OFMSW and a mixture of the grey fraction of MSW, MS (mechanically sorted)-OFMSW, and sludge, respectively [37]. Higher biogas yields are generally obtained with SC-OFMSW or SS-OFMSW than those from MS-OFMSW. The digestate of MS-OFMSW is difficult to handle and should be disposed of in landfills or incinerated [37].

3.2. Inoculation

Inoculation of fresh feedstock is required in a SS-AD reactor to speed up the reaction processes. It is a much faster process than in a landfill, but slower than in liquid AD [39]. Mata-Alvarez et al. found that the effective percentage of inoculation for acidogenic fermentation of organic urban wastes in a plug-flow system was approximately 30% (w/w) [40]. While reducing the amount of inoculum required in a SS-AD reactor will increase the reactor's utilization efficiency, it will also increase the retention time. The digestate or leachate of SS-AD can be recycled to inoculate the fresh feedstock. An increase in the production of VFAs from lignocellulosic feedstock has been observed when rumen fluid was

used as inoculum in SS-AD [41–44]. The rumen bacterium *Fibrobacter succinogenes* plays a major role in the liquefaction of fiber [25].

Kivaisi and Eliapenda [45] reported that a conversion efficiency of 50–70% was obtained when bagasse and maize bran were used as substrates using rumen microorganisms in a semi-continuous AD process. Camp et al. [46] reported that the conversion efficiency of rye straw and reed was less than 45% when they were inoculated with rumen microorganisms. The lignin content of biomass feedstock is a major factor that affects the conversion efficiency of SS-AD process. The lignin content of maize bran and bagasse was only 2.6 and 8.9% by weight, respectively, whereas the lignin content of rye straw and reed was approximately 16% by weight.

3.3. Solids content

An optimized SS-AD process is able to treat more waste in terms of dry mass than a liquid AD plant of the same size. The initial substrate concentration influences the mesophilic anaerobic digestion of OFMSW at batch conditions. A 2008 study found that when the total solid concentration increased from 20% to 30%, the COD removal of the SS-AD decreased from 80.69% to 69.05%. The methane yield at 30% solids content was 17% less than that at 20% solids content [47].

3.4. Temperature

As SS-AD under mesophilic conditions exhibited a poor start-up performance, thermophilic operation of AD was developed later and it has been established as a reliable and accepted mode of SS-AD. Operating SS-AD systems at thermophilic conditions (55 °C) can accelerate the AD process [48]. It also provides the added benefit of increased pathogen reduction during the anaerobic phase. The added amount of heat required for thermophilic operation can be offset by the higher gas production yields and rates [2].

Thermophilic operations have been proved to be a reliable and acceptable option for digestion of organic urban wastes [49,50]. There is also considerable interest in applying SS-AD at thermophilic conditions (55 °C) to treat the organic fraction of municipal solids waste (OFMSW) [51]. The biogas yield of anaerobic digestion of OFMSW at thermophilic conditions is much higher than that in mesophilic conditions [52].

3.5. C/N ratio

Most of the literature recommends an operating C/N ratio range of 20/1 to 30/1 with an optimal ratio of 25/1 for anaerobic bacterial growth in an AD system [36,53]. Improper C/N ratios could result in high total ammonia nitrogen (TAN) released and/or high VFA accumulation in the digester. Both TAN and VFAs are important intermediates and potential inhibitors in the AD process [53]. High concentrations of TAN and VFAs in the digester would decrease the methanogen activity and cause possible failure of the AD process [54].

The optimal C/N ratio varies with the type of feedstock to be digested. Yen and Brune [54] used waste paper to balance the high nitrogen concentration of algal sludge for methane production and results showed that the optimized C/N ratio for the co-digestion was 20/1 to 25/1. Romano and Zhang [55] recommended the C/N ratio be maintained at 15 for the co-digestion of onion juice and digested sludge. When corn stover was inoculated with digested sewage sludge, the digestion process worked well with a C/N of 15 to 18 but failed with a C/N of 21 or higher because the pH dramatically decreased in the first 7 days at 37 °C [56].

4. SS-AD reactor configuration

Different methods for operating SS-AD systems have been developed over the past 20 years in Europe with varying degrees of success. Both continuous and batch reactor systems are in use to treat OFMSW. Developed and marketed by different European-based companies, the Valorga, Kompogas, or Dranco SS-AD systems are the most prevalent and have been mainly used for commercial processing of MSW, kitchen waste, or yard waste. In total, over 75 facilities use one of these process technologies and 24 of these have been in operation for 10 years or longer. The total solids content in the reactor ranges from 20% to 40% and these reactors are operated in continuous single stage and at mesophilic or thermophilic conditions. The biogas yield of the systems ranges from 0.3 to 0.5 m^3/kg volatile solids (VS) [3].

Continuous process reactors function on the principal of adding waste to the reactor at regular intervals and removing an equal amount of finished product. SS-AD reactors in this category are designed as plug-flow, in which the digester contents are not completely mixed, but move as a plug through the reactor from the feed port to the exit, like stuffing a sausage casing. This process requires heavy process equipment that can handle dry, viscous material that does not flow freely. This type of reactor maintains at least 20% solids in the tank. At lower solids content, sediment can quickly accumulate in the reactors. Several continuous process reactors including Valorga, Kompogas, and Dranco are discussed below.

The Valorga process, now owned by Valorga International, uses vertical steel tanks with a central baffle that extends two thirds of the way through the center of the tank. The material is forced to flow around the baffle from the inlet to reach the outlet port on the opposite side, creating a plug-flow in the reactor. These tanks can operate between 25% and 35% total solids. A biogas mixing system is used to create local mixing in the tank. The biogas mixing provides adequate interaction between fresh product and mature digestate. As a result, fresh feedstock does not necessarily require inoculation with finished product or leachate outside the tank prior to feeding. Process water is recycled to reach a target of 30% solids inside the reactor [57]. Biogas mixing is often cited as a limitation of this process, as the gas nozzles inside the tank can clog.

The Kompogas process was developed by W. Schmid of Glattbrugg, Switzerland in the 1980s. The Kompogas reactor is a horizontal steel tank with slowly rotating axial mixers that assist in conveying the material from the inlet to the outlet, keep heavy solids in suspension, and degas the thick digestate. The total solids in the reactor are held in the range of 23–28% to facilitate flow. Recycled digestate is mixed with the feed stream to inoculate the material and process water may be added to reduce the solids content.

The Dranco process, marketed by Organic Waste Systems (OWS) of Belgium, uses a vertical silo design with a conical bottom auger discharge for its reactor. The tank has no internal mixing mechanism. Up to 6 parts recycled digestate is blended with 1 part of fresh feedstock prior to being delivered to the top of the tank [3,39]. In effect, the material is mixed outside the tank. This system typically operates with 30% to 40% total solids in the reactor [6].

Although continuous process reactors have dominated the marketplace for SS-AD systems treating MSW, they have not established themselves for the processing of lignocellulosic biomass or energy crops. The primary advantages of batch reactors are their relative simplicity, minimum maintenance requirements, low parasitic energy loss, and, above all, minimum capital cost [58]. Since AD facilities handling biomass are built for farms and for-profit companies, cost and cash flow are of the highest priority. The need for improved economics has driven innovation and development of batch reactors in the past 10 years. And now,

leading batch system technologies are starting to gain entry into the MSW market as well.

In a typical batch system, organic waste or biomass ranging from 30% to 40% TS is digested in a gas-tight container or room. The dry stackable waste is inoculated with finished digestate from the previous batch. To reduce the amount of inoculum needed, leachate can be collected from the reactor and reapplied to the material. Systems that recycle leachate into the reactor vessel are called percolation systems. Leachate recycling enables the colonization of the bacteria throughout the digester by providing a passive transport mechanism for microbial communities. This reduces the amount of digested material needed to inoculate the fresh feedstock before loading the digester. The leachate may also be mixed with fresh material to directly inoculate it without any digested solids being added. This provides the operational benefit of reduced handling costs and higher reactor volume utilization. However, the continual reapplication of leachate will produce a wetter digested product than systems using recycled digestate. The digested material may need to be processed after digestion to reduce the moisture content and stabilize the product.

The German company Bekon has the largest share of the batch digesters in operation. Their 'garage-type' percolation batch reactor is in use for energy crops, MSW, and yard waste. Garage-type digesters with percolation are used by several other system providers. The rectangular reactor is formed in-place as a concrete building. The building has at least three reactor bays to stagger the batch loading of material and achieve a constant overall gas production. The rectangular bays can be built to handle nearly any volume of feedstock. A gas-tight door provides access to the bay for feedstock to be loaded into the reactor by a wheel loader.

Since methane gas forms an explosive mixture with air at a concentration of 15% or higher, the air in the reactor must be evacuated after filling, and the methane gas in the reactor must be purged before opening. Carbon dioxide- rich engine exhaust can be used in commercial operations to purge the head before opening. The low BTU gas mixture is flared to prevent the emission of methane into the atmosphere. Since the composition of the gas can be measured by in-process instrumentation, this critical function is automatically controlled by the plant control system.

One drawback of the batch system is the lack of control over the biological process. Since the anaerobic degradation proceeds in the pile unencumbered by mixing, the bacteria population will shift in response to the production and population of intermediate metabolites, thereby creating the potential for pockets of concentrated VFAs which lower the pH and inhibit methanogenic activity [3]. Using finished digestate to inoculate fresh feedstock and percolation of leachate mitigates these effects. High process stability is achievable because, even if the system becomes overloaded with volatile organics resulting in an acidic leachate, some areas of the pile will receive a minimal amount of percolate and will be able to slowly regenerate the biology in the entire pile.

5. Conclusion

SS-AD operated at solids concentrations of 15–40% has been widely applied in Europe for the processing of MSW, food waste, and agricultural waste for energy production. Lignocellulosic biomass such as corn stover, wheat straw, rice straw, and leaves can be pretreated with chemical or thermochemical methods before feeding into the SS-AD reactor. A thermophilic temperature is more suitable for SS-AD than a mesosphilic one as the former can produce more biogas and shorten the start-up period without significant increase in energy consumption for heating up. An optimal C/N ratio is necessary to minimize the accumulation of VFAs produced during the fermentation stage and to increase the process stability and biogas yield. Excess VFAs may inhibit the methanogenesis reaction. The major limitations of SS-AD include long retention time and the requirement of digested materials or leachate to inoculate the fresh feedstocks. These challenges can be overcome with the improvement of process and reactor design. As seen in many commercial examples in Dranco, Valorga, or Kompogas reactors, the SS-AD process continues to prove its capability to effectively convert waste material into energy. Continued improvement of continuous and batch SS-AD processes is necessary to treat not only MSW but lignocellulosic biomass such as crop residues and energy crops.

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